

# **Range Systems Simulation for the NASA Shuttle: Emphasis on Disaster and Prevention Management during Lift-Off**

**Luis Rabelo, Jose Sepulveda, Reinaldo Moraga, Jeppie Compton, and Robert Turner**

## **Abstract**

This article describes a decision-making system composed of a number of safety and environmental models for the launch phase of a NASA Space Shuttle mission. The components of this distributed simulation environment represent the different systems that must collaborate to establish the Expectation of Casualties ( $E_c$ ) caused by a failed Space Shuttle launch and subsequent explosion (accidental or instructed) of the spacecraft shortly after liftoff. This decision-making tool employs Space Shuttle reliability models, trajectory models, a blast model, weather dissemination systems, population models, amount and type of toxicants, gas dispersion models, human response functions to toxicants, and a geographical information system. Since one of the important features of this proposed simulation environment is to measure blast, toxic, and debris effects, the clear benefit is that it can help safety managers not only estimate the population at risk, but also to help plan evacuations, make sheltering decisions, establish the resources required to provide aid and comfort, and mitigate damages in case of a disaster.

**Key words:** NASA space shuttle, expectation of casualties, geographical information systems, gas dispersion, blast effects

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## **Introduction**

Range safety is an important task leading up to and during a space launch. Its goal is to provide for the safety of the public on the ground, the astronauts, the workforce, surrounding infrastructure, airborne aircraft and seafaring ships in the vicinity of the spaceport. Estimates of the population at risk are crucial for safety managers to allow planning for a potential disaster. Often this is not a straightforward task to accomplish and the use of decision-support systems based on distributed computer simulations may enable safety managers not only to establish mitigation projects, but also to better understand the different risks associated with range operations.

This team developed a Virtual Range system to support the process of risk estimation and decision making that serves as a prototype of a distributed simulation system. The goal of this system is to study the safety criteria for National Aeronautics and Space Administration's (NASA) current and next generation space vehicles throughout range operations. This system integrates, in a seamless fashion, several models to improve complex systems visualization in a unique collaborative computing environment. It uses:

- A Shuttle launch trajectory model with estimates of probability of failure of the launch through the different stages from liftoff until separation of the solid rocket boosters, which occurs approximately 2 minutes after liftoff
- A blast model
- A toxics/gas dispersion model

- A geographic information systems (GIS)
- A weather information systems

All these models are hosted and integrated with parametric features of the space vehicles and their flight trajectories to compute the Expectation of Casualties ( $E_c$ ) (see Figure 1).

### Take in Figure 1

In this paper, the range is defined to be the volume through which the space vehicle must pass on its way to and from space, along with its projection onto the earth. Among the different operations involved in range support are security, weather, facilities, vehicle processing, and safety. One of range safety's major concerns is the safety of the people within the projection of the range volume onto the earth's surface that may be exposed in the event of a disaster. The actual dimensions of the volume and its projection onto the surface depend on the vehicle's speed and direction. As the space vehicle moves, the range encompasses new volumes and leaves behind areas that fall out of range of potential hazards. This makes range safety, like many other operations, have a high level of complexity. Normally, the range safety office is responsible for the study, modeling, analysis and assessment of the exposure to potential launch accidents and the corresponding calculations of  $E_c$ . The effects of toxic gases, debris impacts, and blast overpressures on the population are the primary hazards to be studied.

Toxic gas may be caused by an explosion within the solid rocket booster (Figure 2) fuel which is found on many of today's space vehicles. In addition to the toxic release, vehicle explosions caused by these system failures produce debris hazards and may also create a blast overpressure. The modeling of these effects can take considerable effort. Therefore, the integration of these safety models with flight trajectories, available weather information, and GIS systems may largely benefit the range safety office.

A mishap is simulated by using a Monte Carlo simulation which works by generating random numbers based on the probability of occurrence of certain events (in our case the events refer to those causes which may result in the loss of a vehicle). The probability of each major event was determined in previous work (Sepúlveda et al. 2004). Hosting the range models and vehicle models in a distributed computer simulation system will provide decision support to managerial issues concerning risk.

### Take in Figure 2

The applications of the Virtual Range are very broad; however this article will focus just on determining the  $E_c$  of a population at risk of experiencing exposure to a toxic gas as result of a potential disaster within 120 seconds of a Space Shuttle liftoff and will just touch upon the effects of blast overpressure. This distributed decision-making system can assist safety managers in estimating the population at risk, and as a result, plan for areas to shelter, evacuate, and/or for the resources required to provide aid and comfort and mitigate damages. The toxic gas-related risk is a factor of exposure duration and toxic propellant concentration or dosage that would result in casualties ("Casualty is considered to include either death or injury, of at least 1-day

disability, from the direct effects of an accident” (Anderson and McCaleb, 2004)) to normal and sensitive people in a given population area.

### **The Virtual Range’s Architecture**

The Virtual Range integrates a Geographic Information System (GIS), a population model, gas dispersion/blast effects models, Space Shuttle flight trajectory and reliability and failure models, and weather data. The architecture is modular so that it can be easily applied to any space vehicle models and/or launch operation areas.

The need for a simulation of these factors is paramount. For example, toxic gas impact risk is affected by the variability in the meteorological and launch vehicle parameters, wind uncertainties, and other weather related characteristics. Monte Carlo simulation is also used to determine the go/no go launch decision. For any planned flight path, safety needs to determine the  $E_c$  using the actual conditions (input parameters). These analyses will identify parameters with the largest impact on the value of  $E_c$  and, therefore, identify where modeling accuracy is most critical.

If an accident occurs, the Virtual Range system determines the position of the space vehicle, the impacted volume, weather data and its trends, and initial dispersion velocity of the released pollutants. These values are the input to the Virtual Range dispersion model called CALPUFF (Earth Tech, 1997; Earth Tech, 2002) a multi-layer, multi-species, non-steady state Lagrangian puff dispersion model - which in turn predicts the toxic concentrations of the toxicant at a specified time after the onset of the accident. These values determine the envelope over land where the pollutant concentration exceeds the ceilings imposed by the pollutant’s Exposure Response Functions (ERFs). We use the number of exposed people under that envelope to estimate the number of casualties resulting from exposure to toxic levels of the released toxic propellant for that simulated disaster.

For the  $E_c$  calculation restricted to gas dispersion, we focused on displaying boundaries. We used as a critical value the concentration defined for an  $E_c$  of  $30 \times 10^{-6}$  casualties/launch (i.e., 30 casualties per million flights). This number is widely accepted in the safety community and is the result of a number of legal decisions related to carcinogens causing cancer and is generally accepted by the United States Federal Aviation Administration (FAA). Anderson and McCaleb (2004) state that “this criterion was derived from the principle that the ranges should be operated in a manner that is as safe to the public as general or commercial aviation.” However, this principle is being changed to one that says the launch must be no more hazardous than day-to-day operations.

### **Factors Affecting $E_c$**

This section focuses on the factors that may affect the computation of  $E_c$ .

#### **Flight Path**

For a planned flight trajectory (altitude, speed, direction), the system projects an appropriate “envelope” (i.e., the footprint of the projected impact) for a given risk-component. We focused on released toxic gases and used the CALPUFF model to predict their path and concentration levels.

Figure 3 displays the typical launch sectors for launches from the Eastern Range which includes Cape Canaveral Air Force Station, Kennedy Space Center (KSC), owned or leased facilities on downrange sites such as Antigua and Ascension; and in the context of launch operations, the Atlantic Ocean, including all surrounding land, sea, and air space within the reach of any launch vehicle extending eastward into the Indian and Pacific Oceans).

In general, space vehicles are launched in an easterly direction and on an azimuth that provides protection of land masses and populated areas on and off the facility, including the Caribbean Islands, Bermuda, the Northeast coasts of South America, and Africa.

### **Take in Figure 3**

#### **Space Shuttle Probabilities of Failure**

The second factor is the exact location where the accident occurs. The Virtual Range interface grants the safety official the ability to select a random occurrence for the accident or to “fix” the time or location of the accident. There is also a third time-related option, which is to specify a series of observations at fixed time intervals (for example, at 0, 10, 20, 30, etc. seconds after launch). Monte Carlo simulation works by generating random numbers based on the probability of certain events occurring which are obtained from a comprehensive reliability model developed for NASA (Fragola and Maggio, 1995). This reliability model presents the total probability of losing the space vehicle due to the failure of a Space Shuttle system or subsystem. In order to obtain the probability of losing the vehicle at the different stages during the first 120 seconds we divided that period of time into representative events. We also determined the range of time for each of these events. We next calculated the probability of losing the vehicle as a result of an issue within one of the main components such as the external tank, space shuttle main engine, integrated solid rocket booster, or orbiter (see Figure 2).

With the intention of getting a better estimate of the probability at different stages, Space Shuttle experts were asked to assign weights to represent their best estimate of a failure occurring in a given subsystem during a given time or event of Space Shuttle operation. With this information the total probability was weighted and calculated at each stage within the first 120 seconds.

#### **The Toxic Gas**

In addition to the main engines, the Space Shuttle relies upon two Solid Rocket Boosters (SRBs) to launch the Space Shuttle into space. The SRBs contain aluminum powder as fuel and ammonium perchlorate as its oxidizer. This combination creates 2-Normal hydrochloric acid (HCl) as a major combustion bi-product. Due to its relative high quantity, the expected direction and ground level concentration of the HCl gas is a major determinant considered during launch decisions. During a nominal launch the total exhaust of HCl is 163.3 tons during the first 15 kilometers of flight. About 72.5 more tons are exhausted at higher altitudes in the first two minutes after launch (American Institute of Aerospace and Astronautics, 1992). If a “loss of vehicle” event occurs close enough to lift-off, it is possible under certain meteorological conditions that the ground concentration would exceed 7 ppm, which is the short-term exposure limit (STEL) for HCl for normal people (Hill Brothers Chemical Company, 2001).

Exposure to the HCL gas for normally healthy persons can vary by location and the reaction to the exposure can vary from mild to severe by individual. Mild HCl exposure symptoms include irritation and headache, which are reversible within 48 hours and do not interfere with normal activity or require medical attention (Philipson, 1999). Moderate symptoms include cough and shortness of breath, and medical attention might be necessary. Severe symptoms include disorientation due to constriction of the airway and consequent shortfall in delivery of oxygen to the brain; changes to lung tissue are irreversible in this category. Of course, the STEL values for sensitive people (children, the elderly, and people with asthma or other respiratory diseases) are even smaller and very difficult to predict.

### **The Gas Dispersion Model.**

For the evaluation of the gas dispersion and toxic effect we use CALPUFF, a model developed and distributed by Earth Tech (2002). CALPUFF simulates the effects of time and space by varying meteorological conditions on pollutant transport, transformation, and removal under inhomogeneous and non-stationary conditions. CALPUFF modules allow one to assess toxic effects of specific chemical agents and factors such as variability of meteorological conditions, dry deposition and dispersion over a variety of spatially varying land surfaces, low wind speed dispersion, or wet removal of the pollutant.

There are several factors associated with CALPUFF that may affect the value of  $E_c$ , the most important of which are the initial speed of the toxic plume as it is exhausted, the weather conditions (humidity, temperature, pressure, etc.), the wind speed and direction.

*The Weather Factor.* CALPUFF is accepted by the US Environmental Protection Agency (EPA) as a guideline model used in all regulatory applications involving the long-range (>50km) transport of pollutants. It can also be used on a case-by-case basis in situations involving complex flow and non-steady-state cases from fence-line (near field) impacts out to 50 km. The model consists of three main components (models): CALMET, CALPUFF, and CALPOST. In addition, it also includes several pre-processing programs to interface the model with standard, routinely-available, meteorological, and geophysical datasets.

CALMET is a meteorological model that develops hourly wind and temperature fields on a three-dimensional grid modeling domain with associated two-dimensional fields such as mixing height, surface characteristics, and dispersion properties. Selected temporal and spatial variations in the meteorological fields are explicitly incorporated in the resulting distribution of puffs throughout a simulation period.

CALPUFF contains algorithms for near-source effects such as building downwash, transitional plume rise, partial plume penetration, and sub-grid scale terrain interactions, as well as longer range effects such as pollutant removal (wet scavenging and dry deposition), chemical transformation, vertical wind shear, over-water transport, and coastal interaction effects. It can accommodate arbitrarily-varying point source and grid area source emissions. Most of the algorithms contain options to treat the physical processes at different levels of detail depending on the model application. The primary output files from CALPUFF contain either hourly concentrations or hourly deposition fluxes evaluated at selected receptor locations.

CALPOST is used to process the output files produced by CALPUFF. In addition, CALPOST summarizes the results of the simulation.

*Meteorological Surface Data.* The meteorological surface observations are obtained from the National Oceanic and Atmospheric Administration (NOAA) 2004. These meteorological data files contain near real-time observations of: wind speed, wind direction, temperature (part of surface data file), cloud cover, ceiling height, surface pressure, relative humidity, and precipitation type code.

To improve the accuracy, given the position and code of the station, the meteorological surface data acquires information from nearby weather stations. We used the data from four different stations near Kennedy Space Center.

*Upper Air Data.* This set of observations contain observed vertical profiles of: wind speed, wind direction, temperature, humidity, pressure, and elevation. The data is obtained from NOAA's Radiosonde Database Access.

*Geophysical Data.* This data file contains the geophysical data inputs required by the CALMET model. These inputs include: grid fields of terrain elevations, land use categories, surface roughness length, albedo, Bowen ratio, soil heat flux constant, anthropogenic heat flux, and vegetative leaf area index.

*Over-water Data.* This data is necessary to know the Over-water transport and dispersion. It is necessary to have the following information: air-sea temperature difference, air temperature, relative humidity, over-water mixing high, and wind speed and direction. The location of the over-water site is specified for each observation. The information is taken from the closest buoy, in this case Station 41009 – CANAVERAL which is located 20 nautical miles East of Cape Canaveral. This information is obtained from the National Data Buoy Center, a division of the National Oceanic and Atmospheric Administration (National Data Buoy Center Unedited Surface Weather Observations, 2004).

### **Geographic and Population Models**

The Virtual Range uses ArcGIS, a commercial GIS application from ESRI Corporation that provides data visualization, query, analysis, and integration capabilities along with the ability to create and edit geographic data (ESRI, 2004) to identify the region threatened by the dispersed gas. The area covered in our simulation is basically the area around the Cape Canaveral which includes Brevard and Orange Counties, Florida (USA) and a large part of the sea around Cape Canaveral. The simulation covers about 150 kilometers in each direction from the source (Cape Canaveral). Since this area around Cape Canaveral is a flat, noncomplex terrain and surrounded by sea, the weather data plugged into the model plays an important role in the simulation. It has a good flow of winds along with the pressure and temperature variations across it. The area covered by the simulation is divided into a number of grids with equal spacing to facilitate the study of concentrations resulting from a normal launch or from explosions in the area

considered. Each grid can be a square block, whose side can range from tens of meters to hundreds of kilometers.

The Virtual Range determines the population at risk for a specific risk-component using the LandScan Global Population Database, a public domain database of the world's population developed by the Oak Ridge National Laboratory (ORNL), to present population data associated within the covered region (Oak Ridge National Laboratory, 2004). LandScan includes the best available census counts, usually at province level, for each country and allocates these figures into rural and urban population distributions on a 30" X 30" lat/long grid cell system. To assign values to a specific grid cell, LandScan calculates a probability coefficient for each cell and applies the coefficients to the census counts. The probability coefficient is based on slope, proximity to roads, land cover, night-time lights, and an urban density factor.

The concentration of toxicant within the area under influence is generated as input to ArcView by pre-processing of the Virtual Range model, Monte Carlo model and Calpuff/Calmet/Calpost. The necessary steps to generate the  $E_c$  number and a display of the area of impact are the following:

1. The LandScan population data, in raster format, is imported in the Universal Transverse Mercator (UTM) coordinates.
2. The input text file which includes the area under influence in UTM Coordinates and the ground level concentration of HCl for a particular area of interest are imported on top of the population map as a data layer. Later the two layers are combined to select only the cross areas.
3. The added point of the HCl layer is saved into a feature dataset for query.
4. Then, the query is run on the saved HCl layer to select the region where the concentration of the HCl is 7 ppm, *i.e.*,  $0.0104387 \text{ gm/m}^3$ .

After performing the above steps, the Zonal Statistics function of Spatial Analyst is used to calculate the total number of people affected by 7 ppm of HCl.

Zonal Statistics calculates the statistics for each zone of a zone-dataset based on values from another dataset. A zone is a region in which all the cells in a raster have the same value, regardless of whether or not they are contiguous. The output sum in the zonal statistics gives the total number of people affected in that 7ppm of HCl zone.

### **Exposure Response Functions**

Figure 4 shows the Exposure Response Functions (ERFs) for HCl for sensitive and normal people subject to a 30-minute exposure. The sensitive population was defined as children through age 14 and adults aged 75 and over, as well as all others with respiratory illnesses. In Brevard County, recent census data shows that 42% of the population is composed of those either 18 and younger or 65 and older; this number is expected to increase to about 55% by the year 2010 (United Way of Brevard County, 2002). These curves show that concentrations of 15 ppm and 41.5 ppm of HCl result in an expectation of casualties of about 30 in a million launches ( $E_c = 30 \times 10^{-6}$ ) for sensitive and normal people, respectively.

#### **Take in Figure 4**

ERF curves have been computed for nitric acid, nitrogen dioxide, and hydrochloric acid (Philipson, 1999). They were constructed by a panel of about 20 expert toxicologists who provided best estimates of the 1 and 99-percentiles of expected casualties. Below the first percentile, “essentially no one in a population of a given sensitivity category would be affected to a given level of severity.” Above the 99th percentile, “essentially everyone in the population would be so affected.” Twelve estimates, with ranges of uncertainty, for each substance and duration of exposure (10, 30, 60, and 120 minutes) were provided by members of the panel of experts: one for each percentile, casualty type (mild, moderate, and severe), and victim type (sensitive, normal). Some of the panelists computed duration estimates from 1-hour estimates according to Haber’s Law, which states that “an effect level is directly proportional to exposure concentration multiplied by time” (Philipson, 1999). Once these estimates were decided upon by the panel, ERF curves were then calculated as cumulative distributions.

#### **Geographic Data Model**

ArcGIS is used along with the LandScan Global Population Database. In this GIS environment, a model of population distribution is integrated with the gas dispersion model to calculate  $E_c$  for that risk component, given there is a loss of the space vehicle. Spatial Analyst, an extension toolset in ArcGIS, is used to generate the query on the HCl data from the Gas Dispersion Model to select the region where the concentration of the HCl exceeds a critical value (see Figure 5).

#### **Take in Figure 5**

Note that Spatial Analyst and LandScan combine to give an estimate of the number of people that may be exposed in the affected area. However, this figure represents an upper limit for the number of people at risk as some people will undoubtedly be able to take cover or flee the region before the gas dispersion reaches it. Still a sensitivity analysis could be done on the proportion of the exposed people that will actually die or be incapacitated as a result of the accident.

#### **Blast Effects**

Among all the prospective hazards resulting from an explosion, those caused by blast overpressure waves are often the most destructive. Thus, in addition to the previous gas dispersion models described, a validation was performed on a hybrid approach to predict blast hazards by simulating explosions of the Space Shuttle after liftoff from launch pad LC-39A at KSC. The hybrid approach was necessary to overcome the limited capability of Blast/FX, the blast modeling software at hand. Blast/FX was developed by Northrop Grumman Mission Systems to determine the effects of explosives against facilities and the people in those facilities. It is based on the TNT equivalency method of blast overpressure prediction (See Figure 6).

#### **Take in Figure 6**

#### **Summary and Conclusions**



The Virtual Range system works as follows: A discrete-event simulator simulates the time of the accident, which is determined by the cumulative probability of an accident occurring in different stages of a launch. Each of these stages has a different duration and chance of accident. Based upon the time of the accident, the model references coordinates for the path of the space vehicle and determines the volume of remaining pollutants from the existing model data file.

These values are the input to CALPUFF, which in turn predicts the toxic concentrations for each toxicant at hourly intervals. These values are entered automatically as a layer into ArcGIS, to determine the envelope over land where the pollutant concentration exceeds the ceilings imposed by the corresponding ERF.

ArcGIS's Spatial Analyst has the ability to determine the number of people covered by the displayed layer. We use the number of exposed people and the parameters resulting from the pollutant's ERF to estimate the number of casualties for a simulated disaster resulting in exposure to toxic levels of the released toxicant. Repeating the procedure through enough simulation runs, we can get enough information to generate an "average" boundary and its associated confidence interval.

The modular architecture of the Virtual Range allows for the analysis of new vehicles (e.g., the Crew Exploration Vehicle being designed by NASA for the exploration of the Moon and Mars (National Aeronautics and Space Administration, 2004)) and the study of other launching sites. In addition, we are in the process of integrating debris and blast models. As a result, safety managers could know more about the number of casualties (fatalities, serious and slight injuries, and uninjured) and the level of damage to buildings and facilities for different scenarios.

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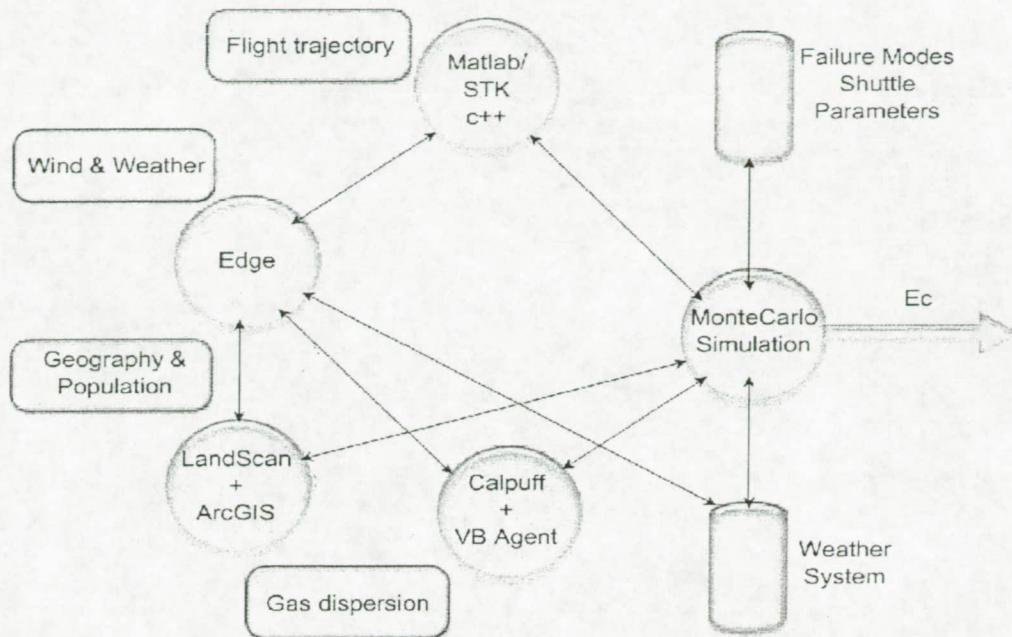


Figure 1. The Virtual Range and its modules (fragmentation and blast capabilities are currently being added).

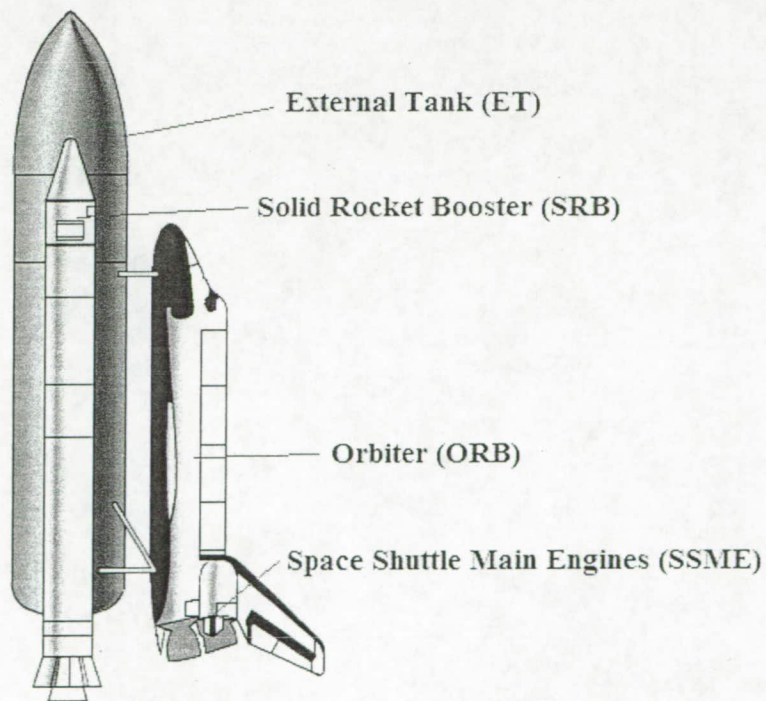


Figure 2. The NASA Space Shuttle in its launch configuration (Adapted with modifications from <http://spaceflight.nasa.gov/shuttle/reference/basics/images>).

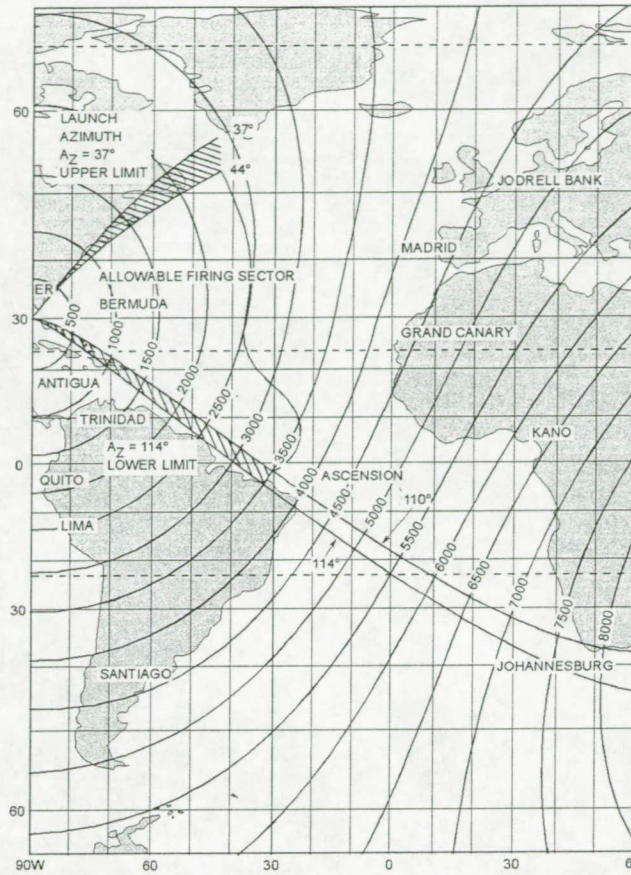


Figure 3. Launch flight corridor, adapted from the Federal Aviation Administration AST Office, 2002. The launch vehicle must stay within the hatched area or the flight will be terminated. .



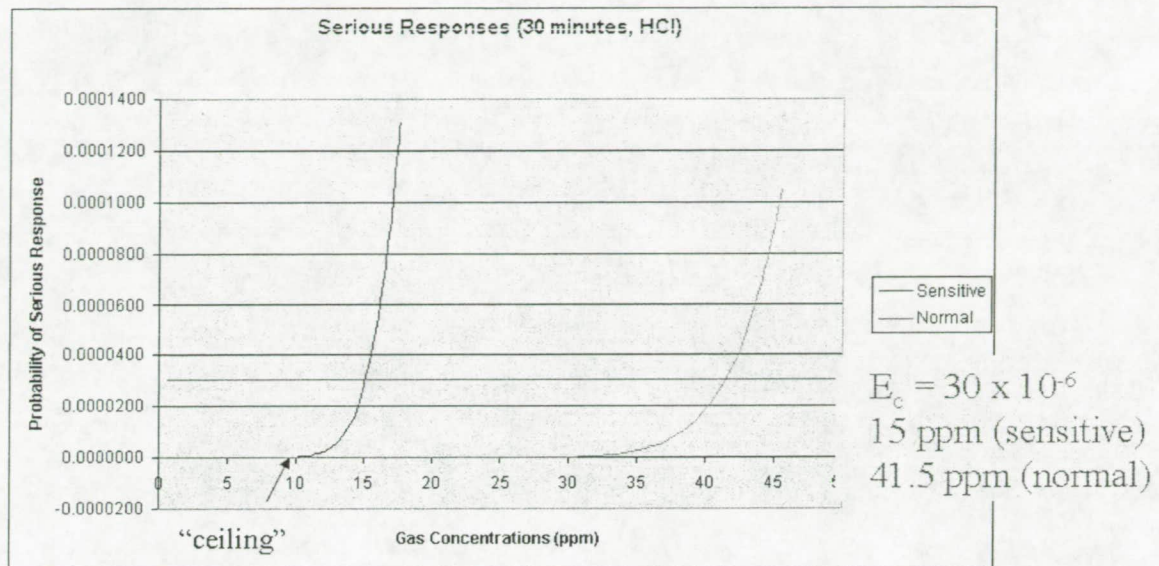


Figure 4. Exposure Response Function for HCl.

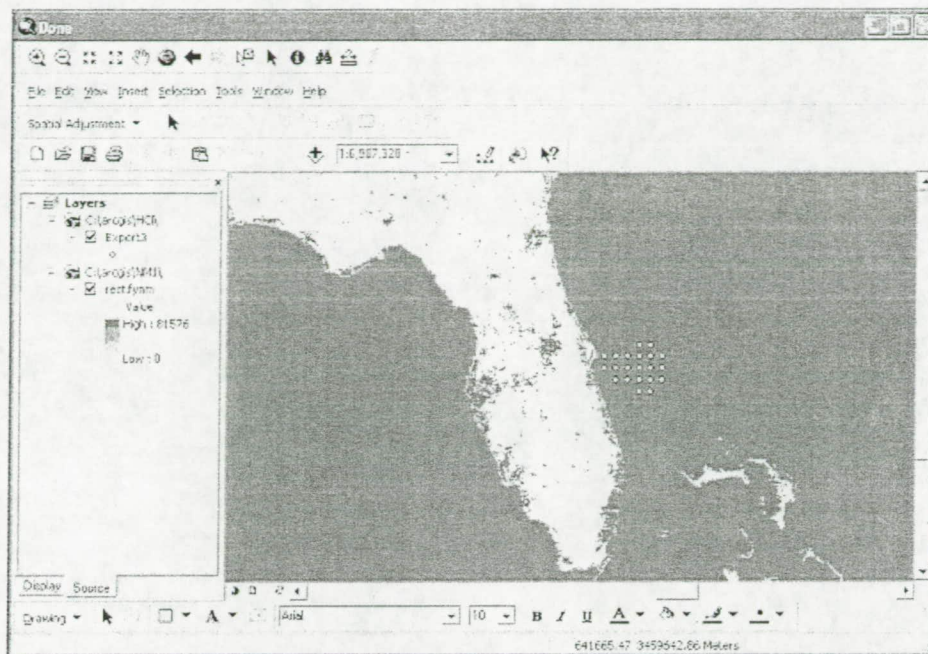


Figure 5. Exercising the Virtual Range system: Output of CALPUFF in ArcGIS from a simulated accident at 34 seconds with specific weather information on October 7, 2002 (2:46 p.m. Central Daylight Time) (Launch Date and Time of NASA Shuttle Atlantis, STS-112 (Space Transportation System – Mission 112)).



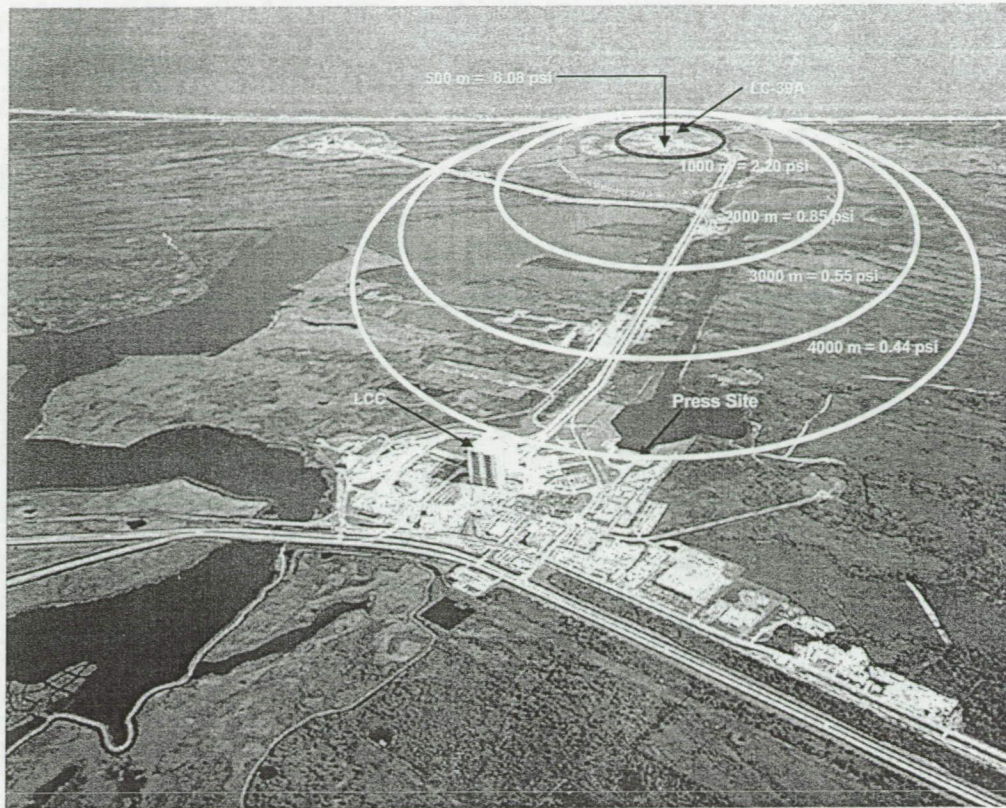


Figure 6. Depiction of experiments of the blast effects for a NASA Shuttle after liftoff (background adapted from <http://mediaarchive.ksc.nasa.gov/search.cfm>).